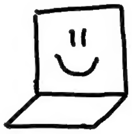
NETWORKING! ACK!

A COMPUTER NETWORKING ZINE!

BY JULIA EVANS!

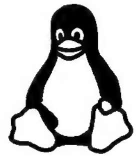
cast of characters

in your house



your laptop (that you use to look at cats)

your program



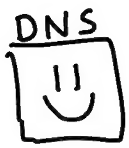
operating system (knows how to do networking)

your home router

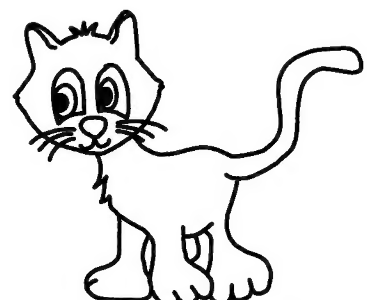
computers you'll talk to

jvns.ca

server (has cat picture)

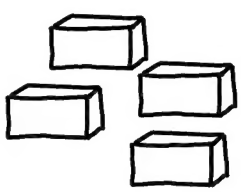


DNS server (knows which server hosts jvns.ca)

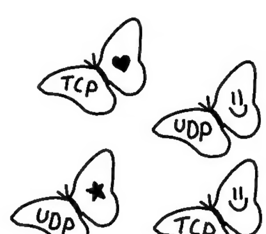


the cat picture we're downloading

in the middle



intermediate routers on the internet



packets!

What's this?!

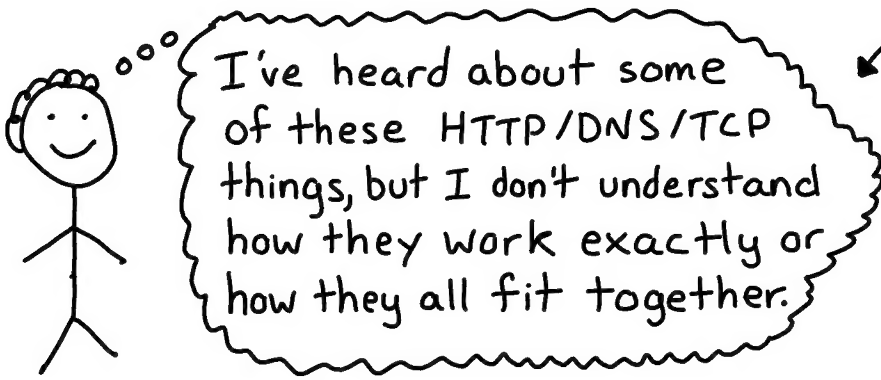
Hi! I'm Julia.

I put a picture of a cat on the internet here:

☆ jvns.ca/cat.png ☆ (go look!)

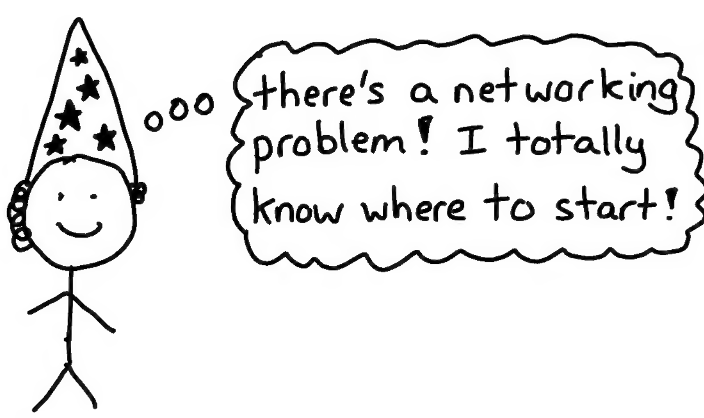
In this zine, we'll learn everything (mostly) that needs to happen to get that cat picture from my server to your laptop.

My goal is to help get you from:



me after I'd been working as a web developer for a year

to...

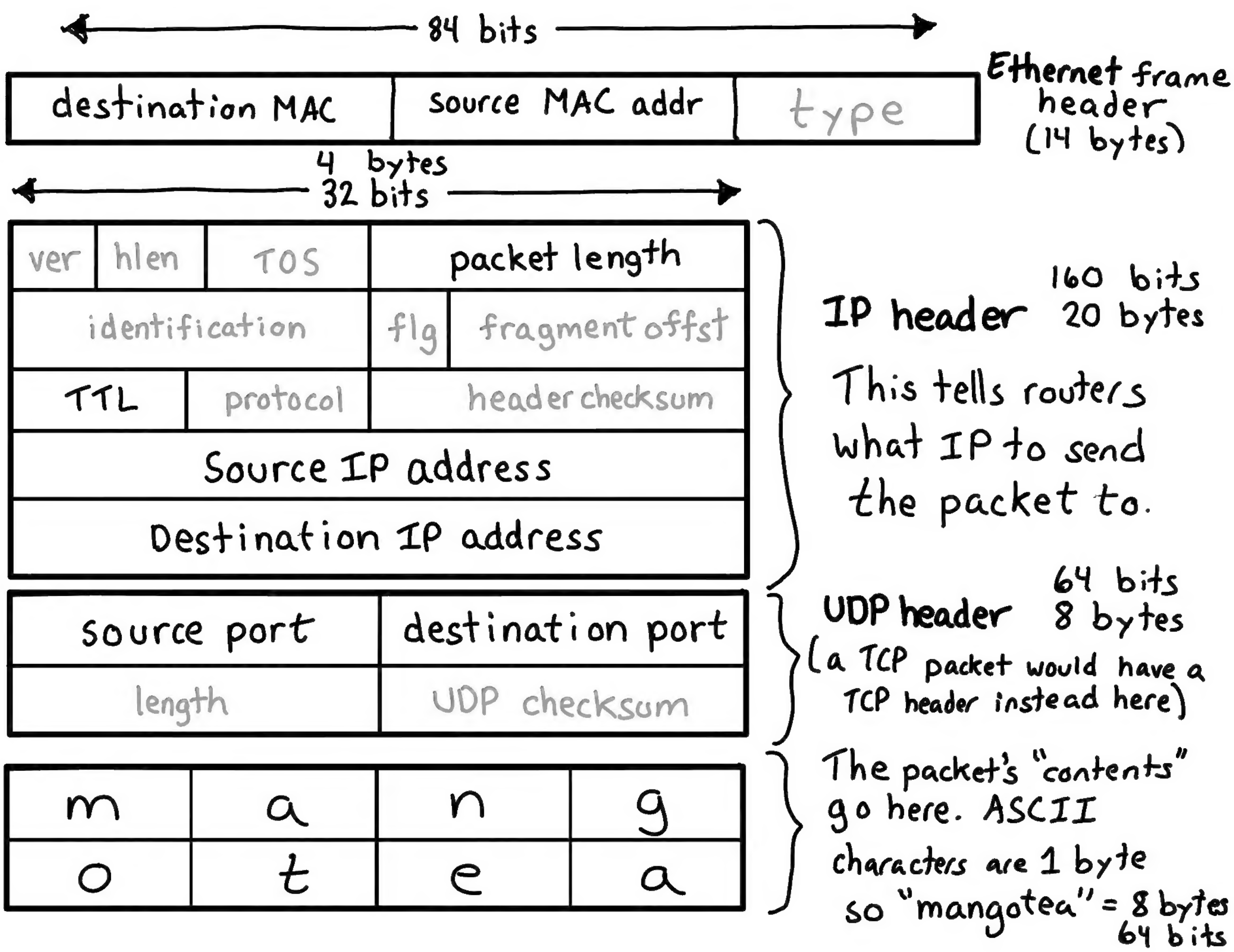


me now

our star: the packet

All data is sent over the internet in {packets}. A packet is a series of bits (01101001...) and it's split into section (aka "headers").

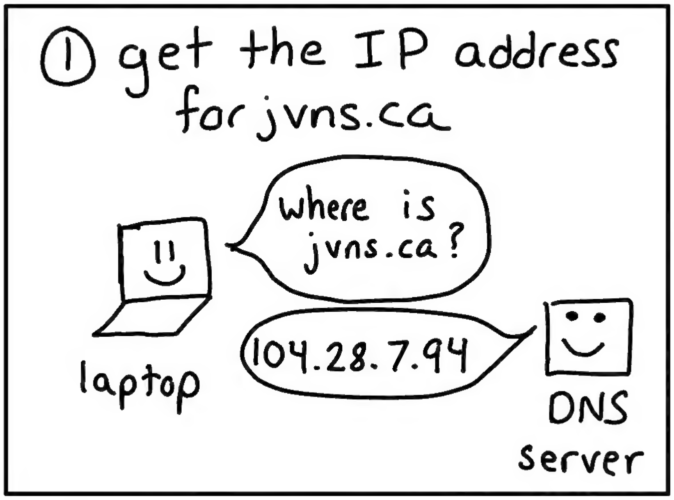
Here's what a UDP packet that says "mangotea" looks like. It's 50 bytes (400 bits) in all!

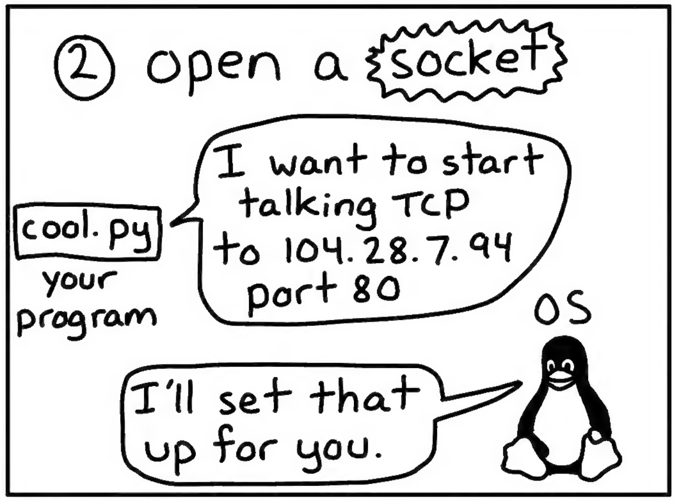


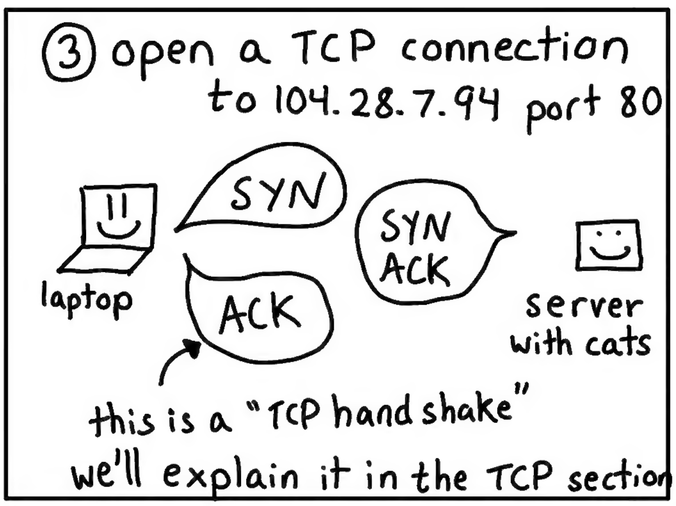
steps to get a cat picture

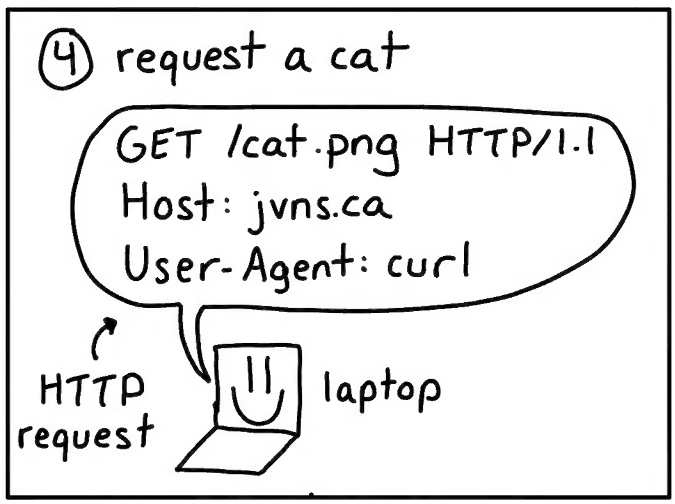
from jvns.ca/cat.png

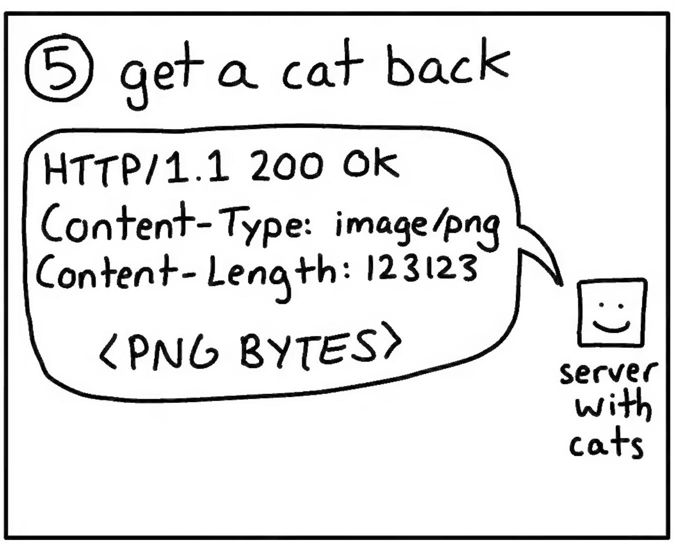
When you download an image, there are a LOT of networking moving pieces. Here are the basic steps, which we'll explain in the next few pages.

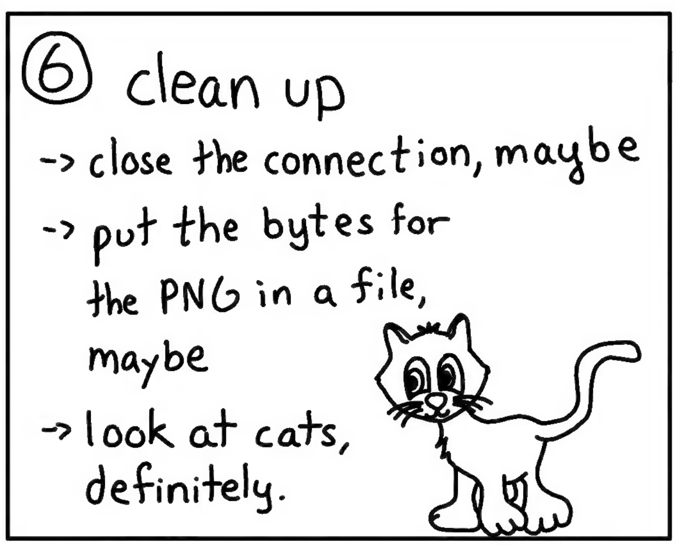










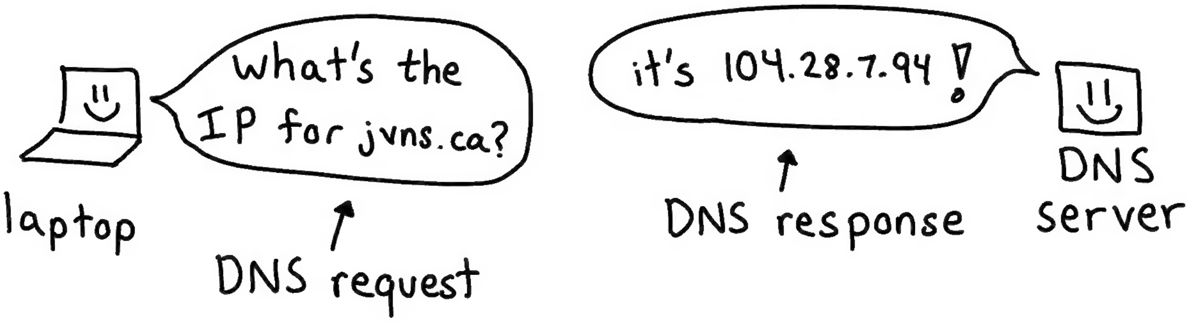


DNS

Step ①: get the IP address for jvns.ca

All networking happens by sending packets. To send a packet to a server on the internet, you need an IP address like 104.28.7.94.

jvns.ca and google.comare domain names. DNS (the "Domain Name System") is the protocol we use to get the IP address for a domain name.



The DNS request & response are both usually UDP packets.

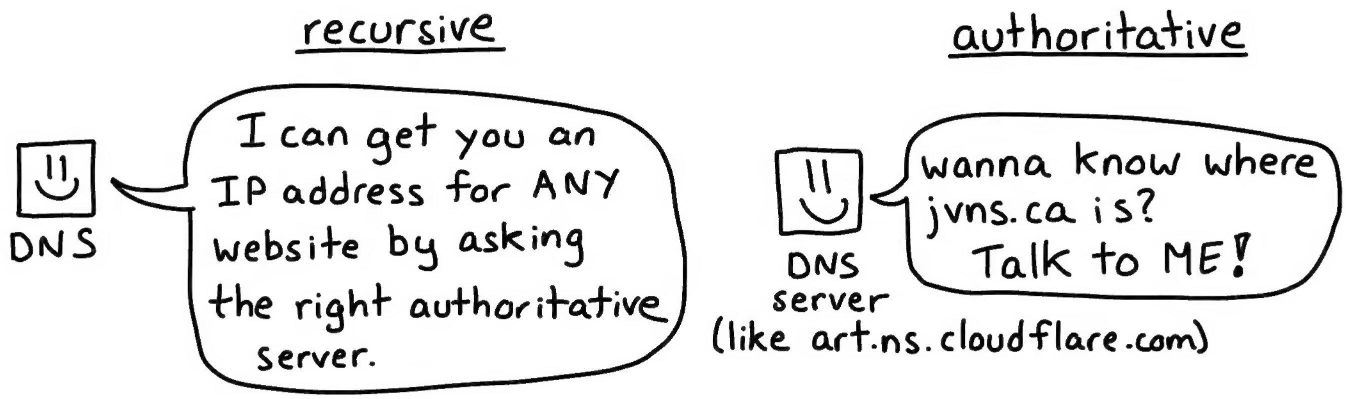
When you run `$ curl jvns.ca/cat.png`:

curl calls the `getaddrinfo` function with `jvns.ca`	`getaddrinfo` finds the system DNS server (like 8.8.8.8)	`getaddrinfo` makes a DNS request to 8.8.8.8	IP address: obtained! 104.28.7.94

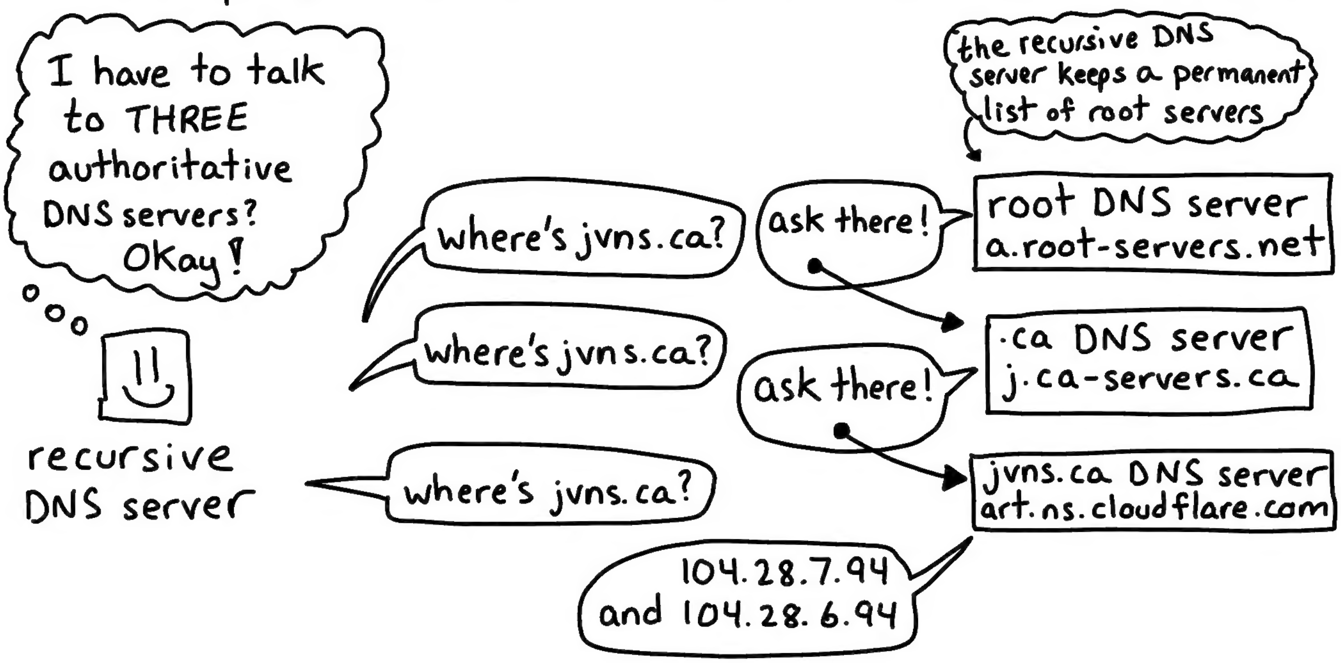
Your system's default DNS server is often configured in `/etc/resolv.conf`.

8.8.8.8 is Google's DNS server, and lots of people use it. Try it if your default DNS server isn't working!

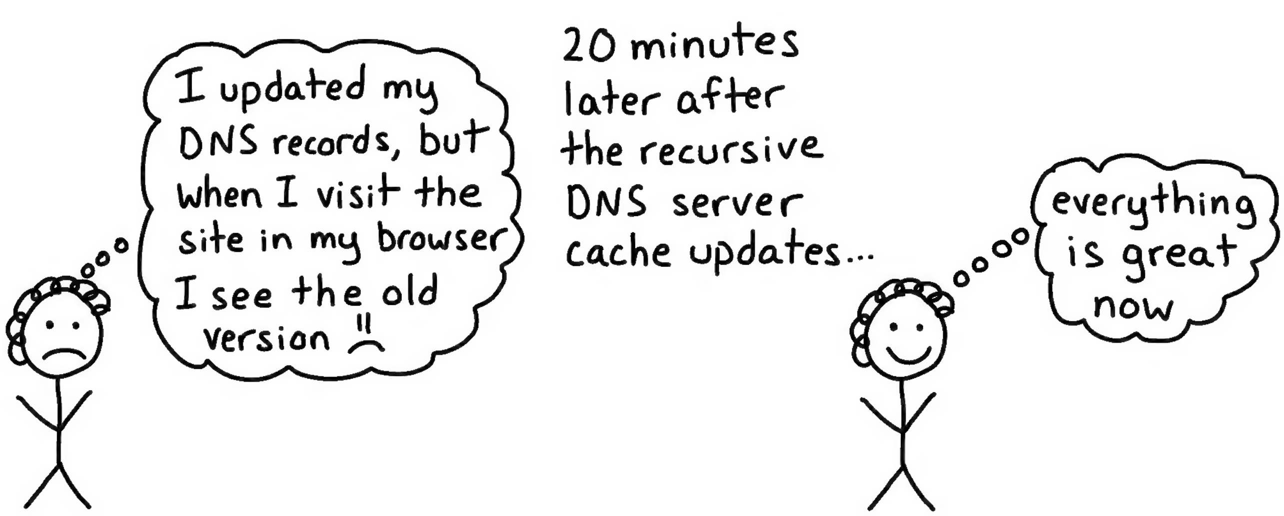
There are 2 kinds of DNS servers:



When you query a recursive DNS server, here's what happens:

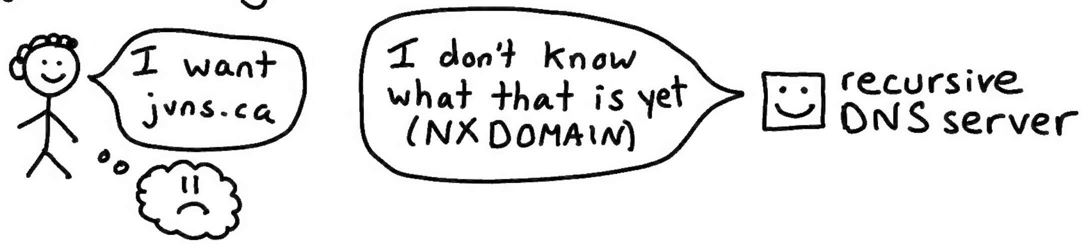


Recursive DNS servers usually cache DNS records. Every DNS record has a TTL ("time to live") that says how long to cache it for. You often can't force them to update their cache. You just have to wait:



let's make DNS requests

When you're setting up DNS for a new domain, often this happens:



Here's how you can make DNS queries from the command line to understand what's going on:

```
$ dig jvns.ca

    ;; ANSWER SECTION
    jvns.ca 268 IN A 104.28.6.94
    jvns.ca 268 IN A 104.28.7.94
```

this record expires after 268 seconds

an "A" record is an IP address

there can be lots of IP addresses for one domain

```
    ;;SERVER  127.0.1.1#53
```

the DNS server I'm using

```
$ dig @8.8.8.8 jvns.ca
```

8.8.8.8 is Google's recursive DNS server. @8.8.8.8 queries that instead of the default.

```
$ dig +trace jvns.ca

        .  502441  IN NS h.root-servers.net
      ca.  172800  IN NS c.ca-servers.net
jvns.ca.   86400   IN NS art.ns.cloudflare.com
jvns.ca.   300     IN A  104.28.6.94
```

root DNS server!

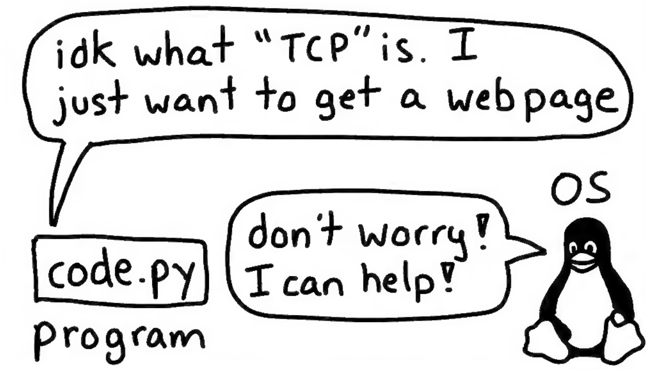
these are the 3 authoritative servers an authoritative server has to query to get an IP for jvns.ca

dig +trace basically does the same thing a recursive DNS server would do to find your domain's IP.

sockets

Step ②: Now that we have an IP address, the next step is to open a socket! Let's learn what that is.

your program doesn't know how to do TCP



what using sockets is like

step 1: ask the OS for a socket

step 2: connect the socket to an IP address and port

step 3: write to the socket to send data

4 common socket types

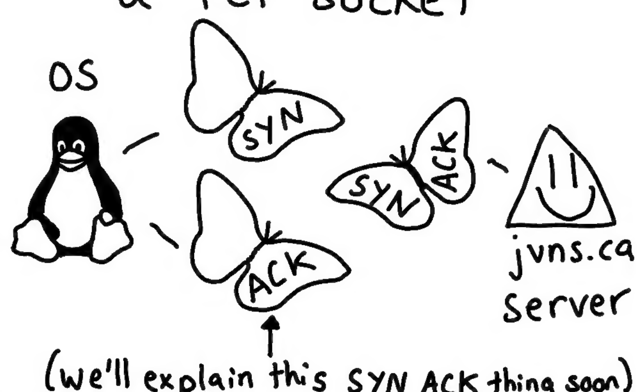
TCP — to use TCP

UDP — to use UDP

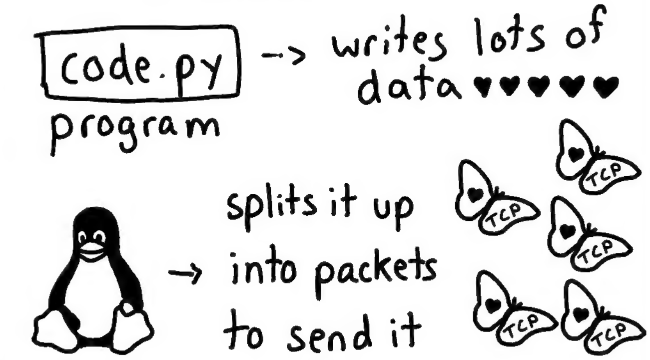
raw — for ULTIMATE POWER. ping uses this to send ICMP packets.

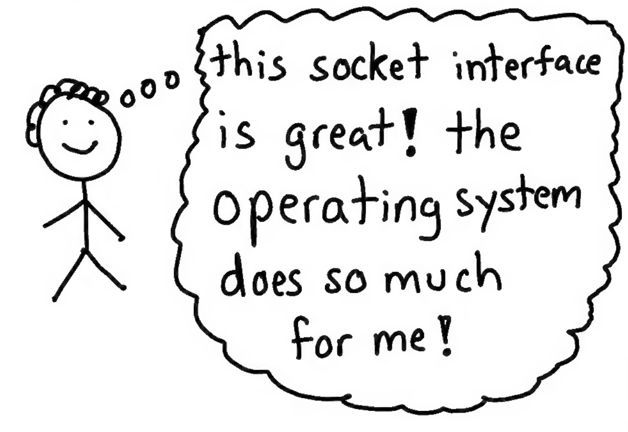
unix — to talk to programs on the same computer

when you connect with a TCP socket



when you write to a socket

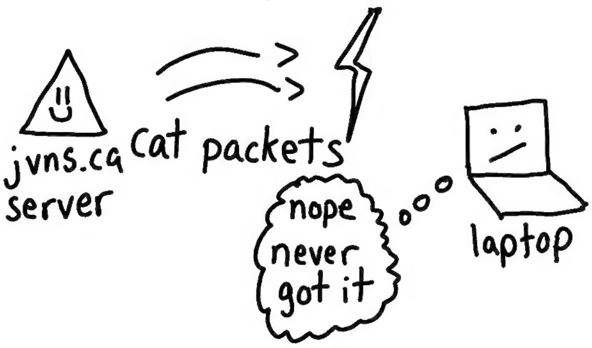




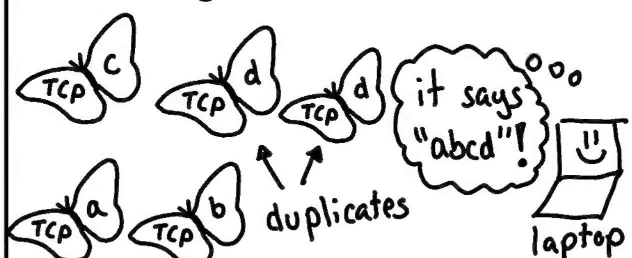
TCP: how to reliably get a cat

Step 3 in our plan is "open a TCP connection!"
Let's learn what this "TCP" thing even is

When you send a packet, sometimes it gets lost



TCP lets you send a stream of data reliably, even if packets get lost or sent in the wrong order.



how does TCP work, you ask? WELL!

how to know what order the packets should go in:

Every packet says what range of bytes it has.

Like this:

once upon a ti ← bytes 0-13
agical oyster ← bytes 30-42
me there was a m ← bytes 14-29

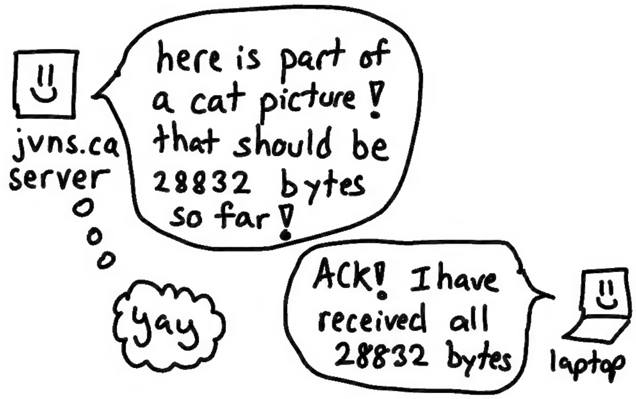
Then the client can assemble all the pieces into:

"once upon a time there was a magical oyster"

The position of the first byte (0,14,30 in our example) is called the "sequence number".

how to deal with lost packets:

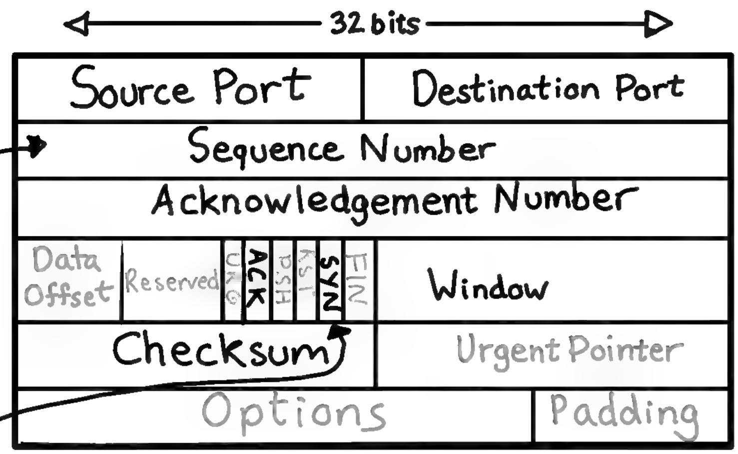
When you get TCP data, you have to acknowledge it (ACK):



If the server doesn't get an ACKnowledgement, it will retry sending the data.

The TCP handshake

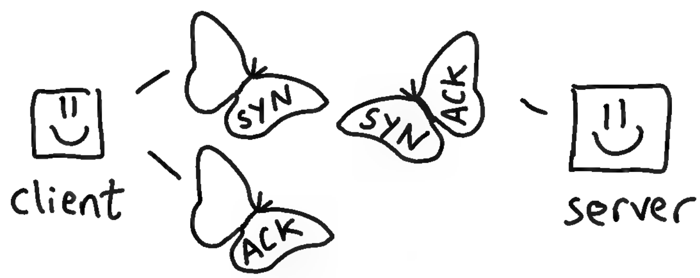
This is what a TCP header looks like:



the "sequence number" lets you assemble packets in the right order ☺

this is the SYN bit

Every TCP connection starts with a "handshake". This makes sure both sides of the connection can communicate with each other.



But what do "SYN" and "ACK" mean? Well! TCP headers have 6 single bit flags (SYN, ACK, RST, FIN, PSH, URG) that you can set (you can see them in the diagram). A SYN packet is a packet with the SYN flag set to 1.

When you see "connection refused" or "connection timeout" errors, that means the TCP handshake didn't finish!

Here's what a TCP handshake looks like in tcpdump:

```
$ sudo tcpdump host jvns.ca
 localhost:51104 > 104.28.6.94:80  Flags [S]
 104.28.6.94:80 > localhost:51104  Flags [S.]
 localhost:51104 > 104.28.6.94:80  Flags [.]
```

TCP handshake!

jvns.ca IP address

S is for SYN
. is for ACK

HTTP

Step 4: Finally we can request cat.png!

Every time you get a webpage or see an image online, you're using HTTP.

HTTP is a pretty simple plaintext protocol. In fact, it's so simple that you can make an HTTP request by hand right now. Let's do it!!!

```
$ printf "GET / HTTP/1.1\r\nHost:
          example.com\r\n\r\n"
  | nc example.com 80
```

one line

the `nc` command ("netcat") sets up a TCP connection to example.com and sends the HTTP request you wrote! The response we get back looks like:

```
200 OK
Content-Length: 120321
... headers ...

<html>
<body>
.... more HTML
```

HTTP/2 is the next version of HTTP. Some big differences are that it's a binary protocol, you can make multiple requests at the same time, and you have to use TLS.

important HTTP headers

This is an HTTP request:

```
GET /cat.png HTTP/1.1
Host: jvns.ca
User-Agent: zine
```

The User-Agent and Host lines are called "headers".

They give the webserver extra information about what webpage you want!

the Host header ← my favorite!

Most servers serve lots of different websites. The Host header lets you pick the one you want!

Servers also send response headers with extra information about the response.

More useful headers:

User-Agent

Lots of servers use this to check if you're using an old browser or if you're a bot.

Accept-Encoding

Want to save bandwidth? Set this to "gzip" and the server might compress your response.

Cookie

When you're logged into a website, your browser sends data in this header! This is how the server knows you're logged in.

... and now for even MORE

We've covered the basics of how to download a cat picture now! But there's a lot more to know! Let's talk about a few more topics.

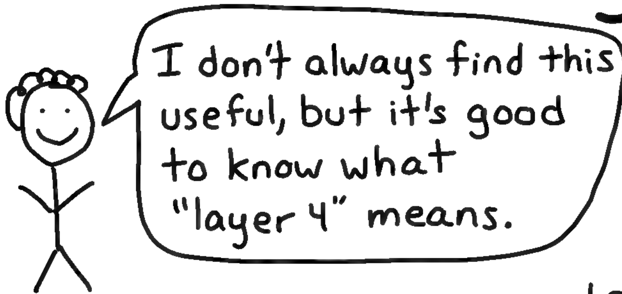
We'll explain a little more about networking protocols:

- → what a port actually is
- → how a packet is put together
- → security: how SSL works
- → the different networking layers
- → UDP and why it's amazing

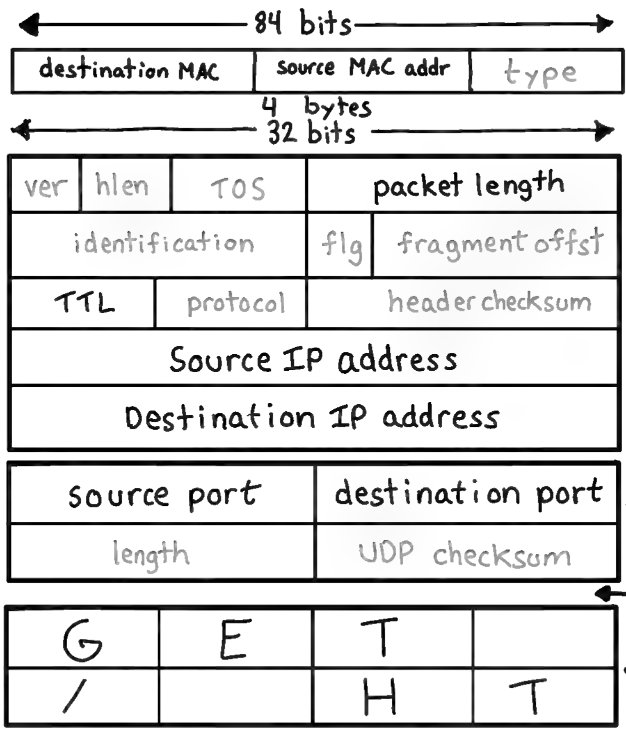
and how packets get sent from place to place:

- → how packets get sent in a local network
- → and how packets get from your house to jvns.ca
- → networking notation

networking layers



Networking layers mostly correspond to different sections of a packet.



Layer 1: wires + radio waves

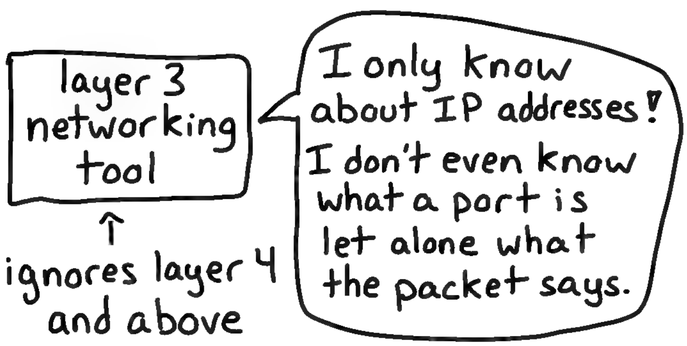
Layer 2: Ethernet/wifi protocol
Your network card understands it.

Layer 3: IP addresses
routers look at this to decide where to send the packet next

Layer 4: TCP or UDP
Where you get your ports!

Layer 5+6: don't really exist
(though they call SSL "layer 5")

Layer 7: HTTP and friends
Routers ignore this layer, mostly. DNS queries, emails, etc. go here.



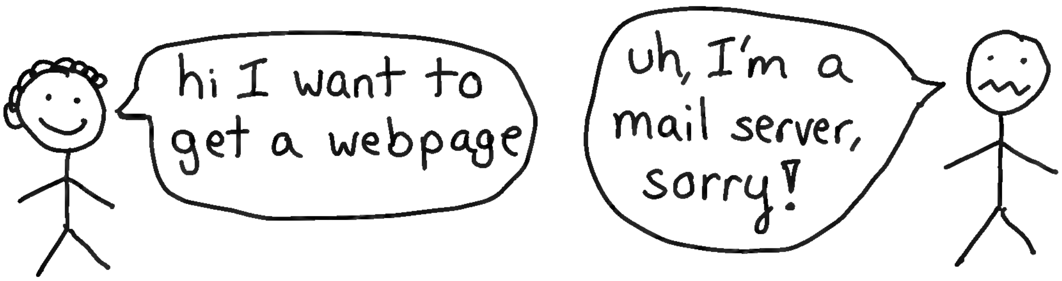
The cool thing is that the layers are mostly independent of each other - you can change the IP address (layer 3) and not worry about layers 4+7.

who uses which layer?

network card	layers 1+2
home router	layers 2+3+4
applications	mostly layer 7 but also layer 4 for the port

what's a port?

ports are part of the TCP and UDP protocols.
(TCP port 999 and UDP port 999 are different!)
When you send a TCP message, you want to talk to a specific kind of program.
This would be bad:



We want to have different kinds of programs on the same server: minecraft DNS email

So every TCP/UDP packet has a port number between 1 and 65535 on it:

netstat and lsof can tell you which ports are in use on your computer

some common ports

DNS:	UDP port 53
HTTP:	TCP port 80
HTTPS:	TCP port 443
SMTP:	TCP port 25
Minecraft:	TCP + UDP port 25565

UDP

user datagram protocol

DNS sends requests using UDP. UDP is a really simple protocol. The packets look like this:

UDP header

~ IP stuff ~

source port	destination port
length	UDP checksum

~ packet contents ~

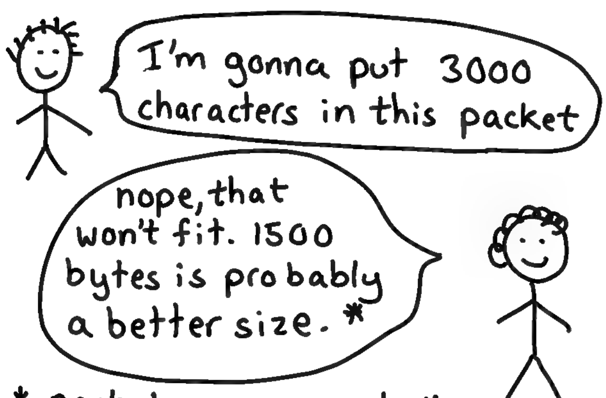
"unreliable data protocol" (not what it really stands for)

When you send UDP packets, they might arrive:

- out of order
- never

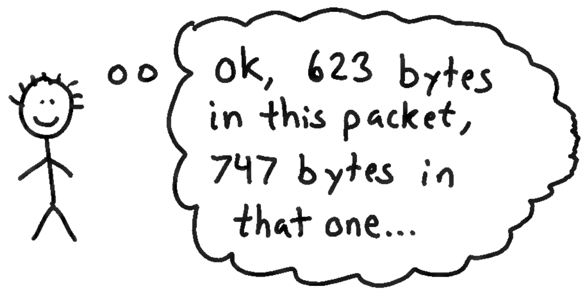
<u>any</u> packet can actually get lost, but UDP won't do anything to help you.

Packet sizes are limited

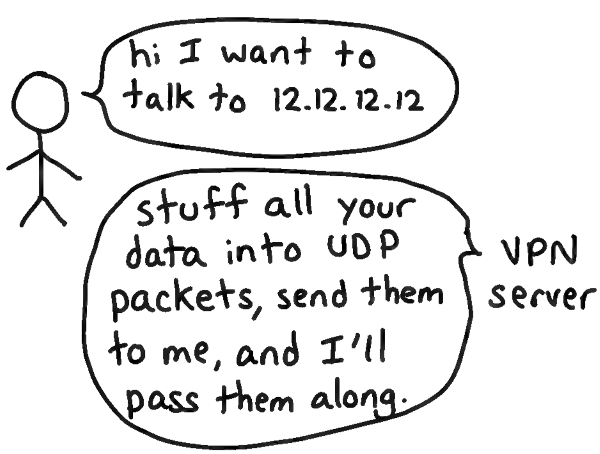


* packet sizes are actually a super interesting topic. Search "MTU".

you need to decide how to organize your data into packets manually



VPNs use UDP



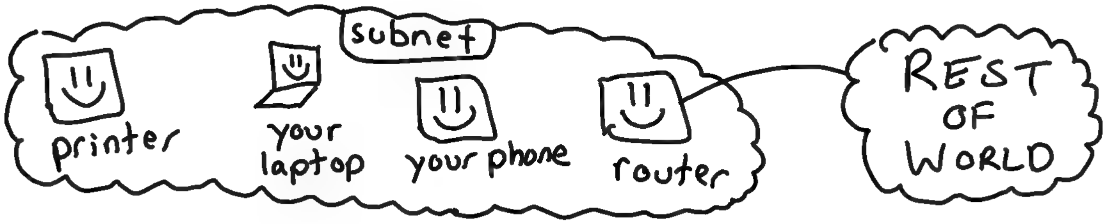
Streaming video often uses UDP

Read http://hpbn.co/webrtc for a GREAT discussion of using UDP in a real-time protocol.

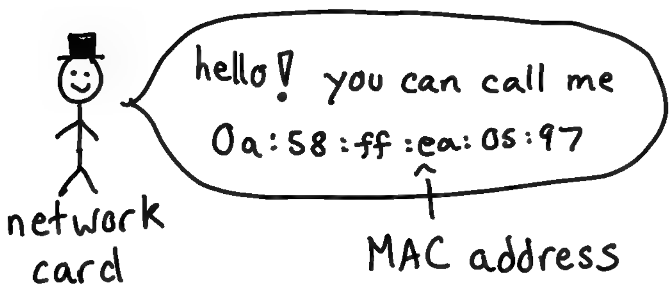
Local networking

aka "how to talk to a computer in the same room"

Every computer is in a <u>subnet</u>. Your subnet is the list of computers that you can talk to directly.

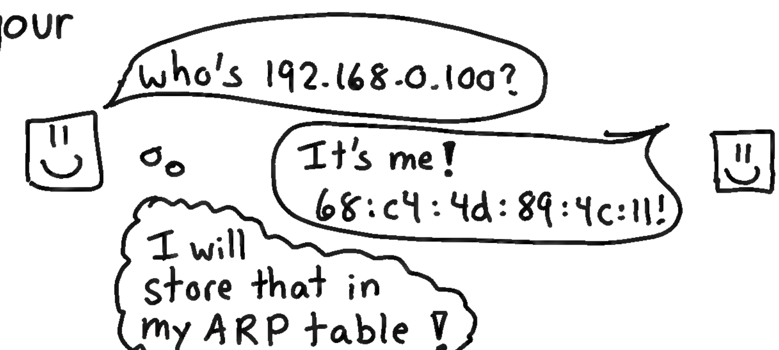


What does it mean to talk "directly" to another computer? Well, every computer on the internet has a network card with a MAC address.



Your laptop's IP address changes if you go to an internet cafe, but its MAC doesn't.

When you send a packet to a computer in your subnet, you put the computer's MAC address on it. To get the right MAC, your computer uses a protocol called ARP: "Address Resolution Protocol".



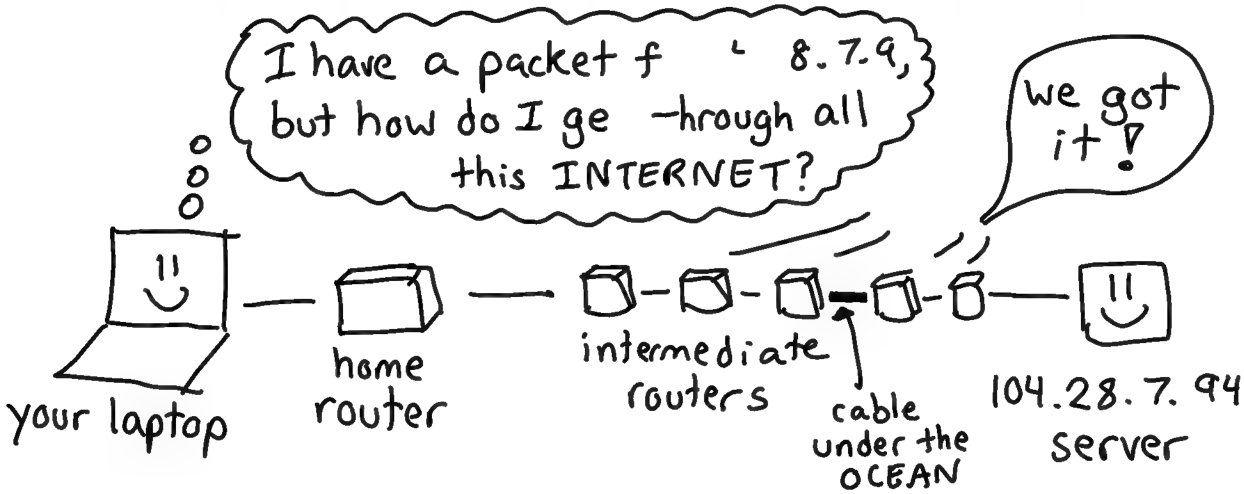
You can run `arp -na` to see the contents of the ARP table on your computer. It should look like this:

MAC for 192.168.1.120 (my printer)

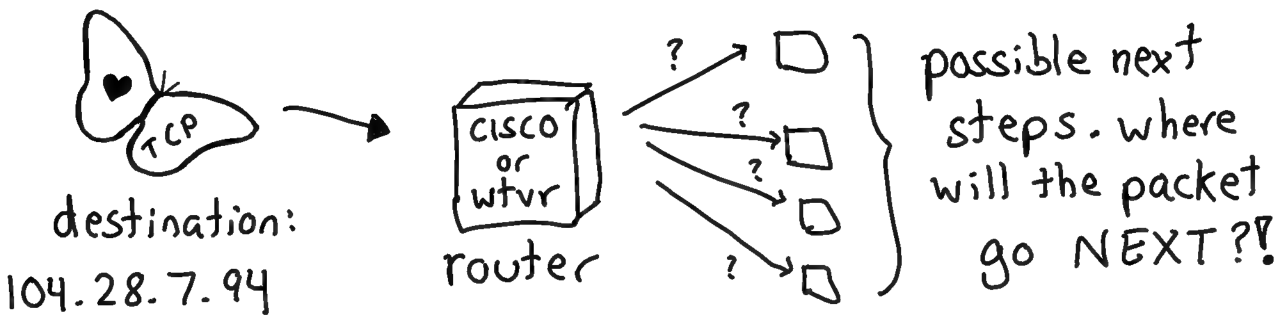
my wifi card

```
$ arp -na
? (192.168.1.120) at 94:53:30:30:91:98:c8 [ether] on wlp3s0
```

How packets get sent across the ocean

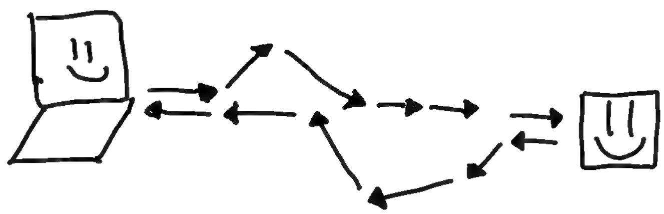


When a packet arrives at a router:



Routers use a protocol called BGP to decide what router the packet should go to next:

A packet can take a lot of different routes to get to the same destination!



The route it takes to get from A→B might be different from B→A.

Exercise:

Run `traceroute google.com` to see what steps your packet takes to get to google.com.

Notation time!

10.0.0.0/8   132.5.23.0/24

People often describe groups of IP addresses using <u>CIDR notation</u>.

example CIDRs

CIDR	range of IPs
10.0.0.0/8	10.*.*.*
10.9.0.0/16	10.9.*.*
10.9.8.0/24	10.9.8.*

important examples

10.0.0.0/8 and 192.168.0.0/16 and 172.16.0.0/12 are reserved for local networking.

In CIDR notation, a /n gives you 2^{32-n} IP addresses. So a /24 is $2^8 = 256$ IPs.

It's important to represent groups of IP addresses efficiently because routers have LOTS TO DO.

router

is 192.168.3.2 in the subnet 192.168.0.0/16? I can do some really fast bit arithmetic and find out!

The IP address 10.9.0.0 is this in binary:

10 ↘ 9 ↘ 0 ↘ 0 ↘

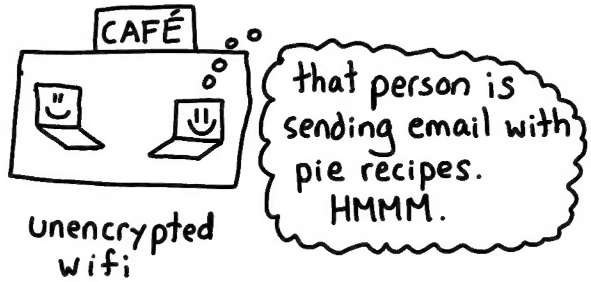
$\underbrace{\text{00001010 00001001 0000000 00000000}}_{\text{first 24 bits}}$

10.9.0.0/24 is all the IP addresses which have the same first 24 bits as 10.9.0.0!

SSL / TLS

(TLS: newer version of SSL)

When you send a packet on the internet, LOTS of people can potentially read it.



SSL encrypts your packets:

old packet

to: 9.9.32.94:443
from: 31.97.1.2:999

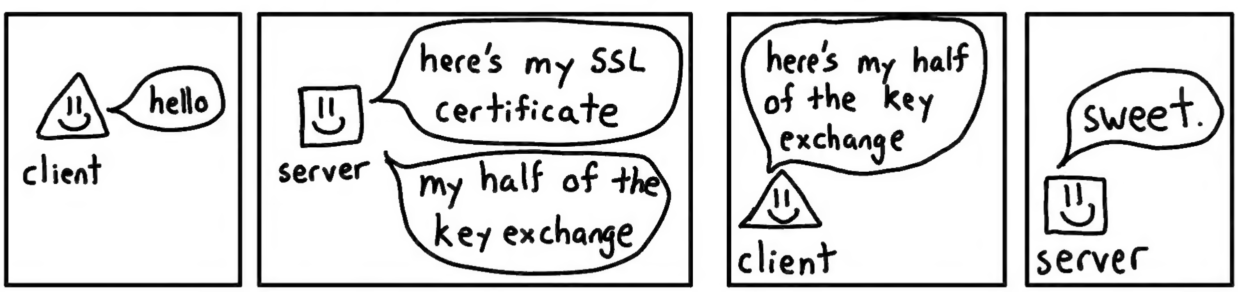
IP address + port stay the same ⟹

new packet

to: 9.9.32.94:443 ← 443 is the usual SSL port
from: 31.97.1.2:999

here is my secret lemon pie recipe ⟹ x 8; ´fae94aex jjb43,8b"5jkk ← nobody's gonna know the secret pie recipe NOW!

What happens when you go to https://jvns.ca:



(very simplified)

Once the client and server agree on a key for the session, they can encrypt all the communication they want.

To see the certificate for jvns.ca, run:

```
$ openssl s_client -connect jvns.ca:443 -servername jvns.ca
```

TLS is really complicated. You can use a tool like SSL Labs to check the security of your site.

wireshark

Wireshark is an amazing tool for packet analysis. Here's an exercise to learn it! Run this:

```
$ sudo tcpdump port 80 -w http.pcap
```

While that's running, open metafilter.com in your browser. Then press Ctrl+C to stop tcpdump. Now we have a pcap!

Open http.pcap with Wireshark.

Some questions you can try to answer:

1. What HTTP headers did your browser sent to metafilter.com?

   (hint: search `frame contains "GET"`)

   How many packets were exchanged with metafilter.com's server?

   (hint: search `ip.dst == 54.1.2.3`) put the IP from ping metafilter.com here

Wireshark makes it easy to look at:

- IP addresses and ports
- SYNS and ACKs for TCP traffic
- exactly what's happening with DNS requests
- and so much more! It's a great way to poke around and learn.

♡ thanks ♡
for reading

If you want to know more about networking:

→ make network requests! play with

dig traceroute tcpdump ifconfig netcat wireshark netstat

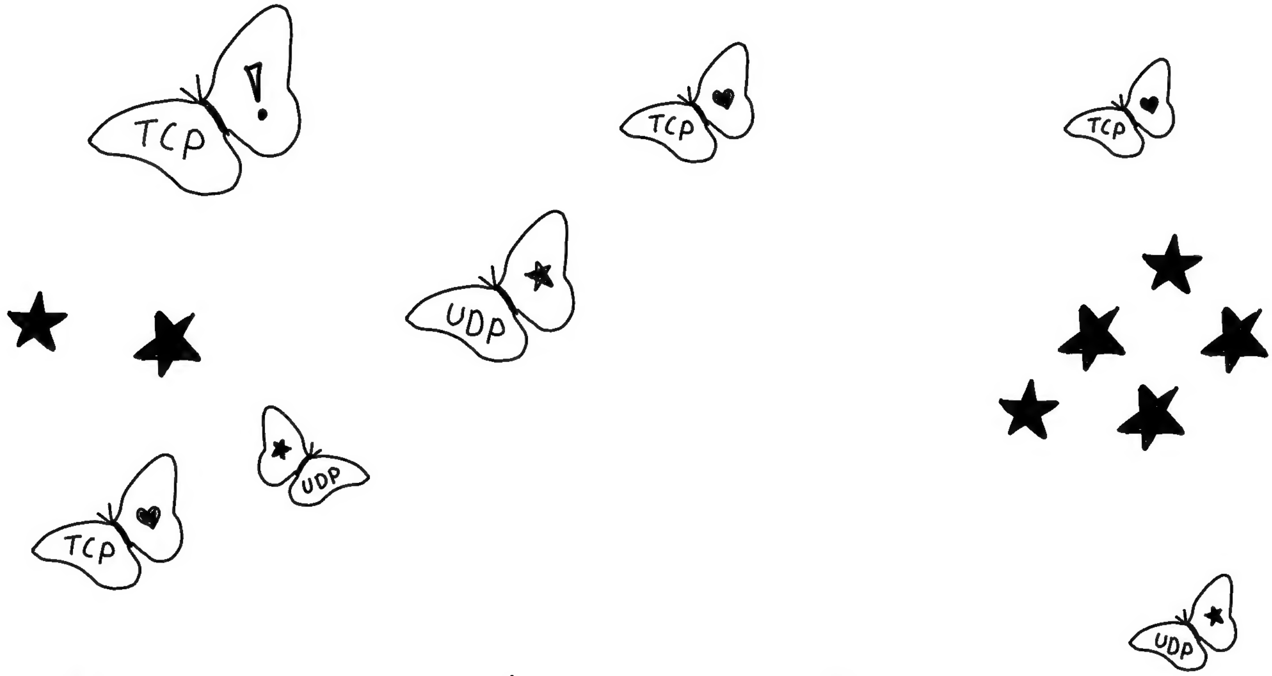
→ beej's guide to network programming is a useful + funny guide to the socket API on Unix systems.

→ beej.us/guide/bgnet ←

→ High Performance Browser Networking is a *fantastic* and practical guide on what you need to know about networking to make fast websites.
You can read it for free at:

→ hpbn.co ←

Thanks for Kamal Marhubi, Chris Kanich, and Ada Munroe for reviewing this!



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